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Economic feasibility of energy recovery from solid waste in the light of Brazil's waste policy: The case of Rio de Janeiro

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ABSTRACT

Energetic waste disposal has tremendous potential for generating alternative (renewable and non-conventional) energy from municipal solid waste (MSW), reducing greenhouse gas emissions, creating socio-economic and environmental benefits, and achieving a sustainable expansion of the energy sector. However, in spite of these tremendous benefits, the Brazilian MSW disposal market remains dominated by landfilling. In total, energetic MSW treatment plants in Brazil are expected to achieve an installed capacity of 12,400 MW by 2020 and 17,550 MW by 2030 respectively. Investments into wind, small-scale hydro, and biomass plants will exceed R$ 69 billions between 2011 and 2020. This paper aims to assess the implications of Brazil's National Policy on Solid Waste (PNRS) on the economic feasibility of different energetic MSW treatment facilities. Therefore, the PNRS is comprehensively analysed, particularly those areas that outline the decision-making criteria for future investments. These criteria are then applied to the specific case of Rio de Janeiro, first by examining the municipality's current state of MSW management and second by examining 20 hypothetical future investment projects into three different energetic MSW treatment technologies. The case study delivers crucial information about the economic feasibility of the considered technologies by addressing specific provisions in the Brazilian legal framework and by applying relevant country-specific financial incentives, designed to encourage investments into renewable energies.

Contents

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1. Introduction

There is an increasing awareness throughout Brazilian society of the need for sustainable municipal solid waste (MSW) management. As a result, the national government is under increasing pressure to redesign their legal frameworks to satisfy a wide range of competing interests. The implementation of modern MSW management has become an increasingly important issue for emerging economies and their policy makers in general, with proponents arguing its potential benefits to human health, environmental quality, general economic sustainability, and other socio-economic benefits [1–3].

According to the recent survey of solid waste in 2009–2010 [4], the annual generation of MSW grew by 6.8% from 57 011 136 tons[2] in 2009 to 60 868 080 tons in 2010, representing a 5.3% increase to 378.4 kg/(hab year). Interestingly, these increases are significantly larger than the country's urban population growth rate of approximately 1% in the same period of observation. At the same time, the yearly amount of MSW collected, which increased by 7.7%, topped 54 million tons in 2010. The related increase in the collection per capita of MSW was about 6.3% to 336.6 kg/(hab year). The difference between the generated and collected amount of MSW in 2010 represents the amount of waste that was improperly disposed of. According to a study [5] carried out by the Brazilian Federal Energy Research Company (EPE) in 2008, the collected amount of MSW treated through recycling amounted to a mere 8% of the total share collected, with composting at 2% and landfilling accounting for the remaining 90%. Both the development over time and the shares of these certain types of landfill are presented in Table 1, reflecting the high proportion of improper final waste disposal via dumps.

Brazil is at present highly dependent on electricity imports and domestic electricity generation through the burning of fossil fuels, which accounted for 35.9 TW h and 78.5 TW h in 2010 respectively. MSW might not only be used to increase the current 4.7% share of biomass on Brazil's domestic electricity supply of 545.1 TW h in 2010 [7]. But, furthermore, it is also well suited for electricity generation close to high-demand areas like fast growing urban centres. A recent expansion plan [8] for Brazil's electricity system, carried out by the Ministry of Mines and Energy (MME), together with EPE, noted that the country's energy system is currently dominated by centralised hydroelectric power plants, but has enormous potential for expansion through renewable energy sources like biomass. This expansion would allow both increased energetic potential and operational benefits such as decentralised electricity generation with relatively high controllability, low-level integration into the power grid, compensation for reduced electricity generation due low hydrological cycles and comparatively short construction periods.

The government recently realised these benefits. Brazil's National Energy Plan 2030 (PNE 2030 [9,10]) states that the energetic use of MSW is an alternative (renewable and non-conventional) energy source with the potential of achieving an installed capacity of 12 400 MW by 2020 and of 17 550 MW by 2030. See Table 2 for details of the considered technologies. However, the current realisation of energetic MSW treatment within Brazil's energy matrix is very poor. According to the Brazilian Electricity Regulatory Agency (ANEEL), the installed biomass[3] capacity across the country totals 431 power plants with a cumulative installed capacity of 8998.6 MW, whereas only 0.85% or 76 308 kW of this total corresponds with the 18 power plants using biogas from landfills as a fuel [11]. These biogas plants are the only energetic waste treatment facilities currently operating in Brazil. This is in spite of the fact that landfill gas projects typically obtain financial benefits from electricity/gas sales as well as from the sale of carbon credits obtained under the CDM[4] regulations. In fact, many of Brazil's open dumping practices and sanitary landfills can be relatively easily upgraded to support biogas production and electricity generation [13–15]. Yet, given the current situation of MSW electrification in Brazil and pending questions with regard to technological, regulative, and institutional challenges, the authors of the PNE 2030 mentioned that the large-scale use of MSW as an alternative energy source cannot be expected before the year 2015.

The total investment needed for the expansion of the country's power plant complex between 2011 and 2020 is estimated at R$ 190 billion [8]. Meanwhile, the investment into “other renewable sources” (wind power, small-scale hydropower, and biomass) is expected to total R$ 69.1 billions, or 36% of total investment costs [8]. Two important investment initiatives aiming to promote biomass are the

[2] Shorthand for tonnes.

[3] Biomass includes sugar cane bagasse, black liquor, firewood, rice husk, and biogas.

[4] The Clean Development Mechanism (CDM) [12] intends to stimulate sustainable development with allowing emission-reduction projects in developing countries to earn carbon credits termed Certified Emission Reduction (CER) credits, each equivalent to one metric ton of CO_2.

Table 1
Final disposal of solid waste in Brazil by 1989, 2000, and 2008. *Source*: [6].

Method of disposal[a]	1989	2000	2008
Dump	88.2	72.3	50.8
Controlled landfill	9.6	22.3	22.5
Sanitary landfill	1.1	17.3	27.7

[a] Quoted values are percentage shares of single, final waste disposal methods (%).

Table 2
Potential of installed capacity (in MW) using MSW in Brazil by 2020 and 2030. *Source*: [10].

Technological options[a]	2020	2030
Landfill gas	1700	2600
Anaerobic digestion	980	1230
Incineration	3740	5280
Optimised combined cycle	5980	8440

[a] Considering a capacity factor of 80%.

Alternative Energy Sources Incentive Program (PROINFA[5]) [16,17] and the *Project Finance* programme of the Brazilian development bank (BNDES) [18]. For example, the biomass sector within PROINFA accounted for the implementation of 21 power plants with an installed capacity of 550 MW, out of the total 2556 MW achieved by the country's 119 power plants[6] in August of 2009. The *Project Finance* programme has led to 30 approved biomass projects between January 2003 and June 2008, totalling an installed capacity of 955 MW and a total investment of R$ 2536.246 millions, with some 79% of this cost backed by the BNDES. Another incentive for investments is that ANEEL (2004) allows, under certain conditions, for renewables to be exempted from both the transmission fee (TUST) and the distribution fee (TUSD) [19,20].

When considering future investments in the energy sector, Brazilian policy makers must consider both the competitiveness of MSW electrification and the considerable advantages of utilising the huge energy potential of its MSW, such as reducing greenhouse gas (GHG) emissions, socio-economic benefits, and the achievement of a sustainable expansion of the energy sector [21–23]. According to a study undertaken in Rio de Janeiro, the MSW sector was responsible for nearly 41% of the city's GHG emissions in 1998 [24]. Through the application of data envelopment and sustainability analysis methodologies, Oliveira et al. [25] proved that the energetic use of waste is the most sustainable input in the short-term, compared to other energy sources.

Given these benefits, this paper's aim is to assess the implications of Brazil's National Policy on Solid Waste (PNRS) for the economic feasibility of different energetic MSW treatment practices. In Section 2, the PNRS will be analysed based on its general statements regarding the management of solid waste in Brazil, and in particular, the parts which form the basis of economic decision-making for future investments into MSW treatment technologies. Subsequently, the policy's decision criteria will then be applied to the specific case of Rio de Janeiro, first by examining the municipality's current state of affairs in terms of MSW management (Section 3), and second by examining 20 hypothetical future investment projects into three different energetic MSW treatment technologies (Section 5).

[5] Launched in 2004 by the MME and Eletrobrás. The programme, its allocation has already expired, demanded power plants to start operation until the end of 2010.

[6] All the power plants incentivised by PROINFA, including the abovementioned "other renewable sources".

2. Energy recovery from solid waste under the terms of Brazil's National Policy on Solid Waste

Introduced in August of 2010, after two decades of debate in the Brazilian Congress, the National Policy on Solid Waste (PNRS) [26] officially defines the responsibilities and innovative tools for the management of several types of solid waste, with which Brazil hopes to equal the European Union (EU) in waste legislation [27]. Because of the requirements on legislation associated with this ambitious goal, the current EU policy is an excellent benchmark for the subsequent analysis of the PNRS [28–30].

2.1. EU waste legislation and the waste hierarchy

When the EU's Waste Framework Directive 2008/98/EC [31] policy came into effect in 2008, it established a general framework for waste management and set the basic waste management plan for the EU [32]. The Waste Framework Directive aims to minimise the negative effects of the generation and management of waste on human health and the environment, allowing greater uniformity in the application of law and incentivising member countries to develop policies to achieve more ambitious goals [29]. It includes new initiatives on recycling and introduces obligatory initiatives with regard to waste prevention for the EU's 27 Member States [30].

As a supra-national institution, the EU influences its member countries through three binding instruments: regulations that are binding in their entirety to the whole community, directives that bind Member States to achieve specific objectives (though allowing some liberties within the implementation process), and decisions that are binding in their entirety to those to whom they are addressed [33]. The main statements of the Waste Framework Directive 2008/98/EC are fixed targets for re-use and recycling, a binding five-stage waste hierarchy, and guidelines for energy recovery from MSW. Article 11 of the Directive states that the preparation for re-use and the recycling of waste from households and similar waste streams will be increased by at least 50% by 2020, and the same operations applied to non-hazardous construction and demolition waste will be increased by a minimum of 70% by 2020. Furthermore, Article 4 defines the waste hierarchy priority order in waste management, policy, and prevention that must be applied by the EU's member countries in order to deliver the best overall environmental outcome leading to management decisions that are compatible with life-cycle thinking [34]. The main purpose of the hierarchy is to classify and rank the possible MSW operations according to their technical and economic viability, protect resources, ensure sustainability, and improve overall environmental and human health, economic and social impacts, listed in descending order below:

(a) prevention,
(b) preparing for re-use,
(c) recycling,
(d) other recovery, e.g. energy recovery, and
(e) disposal.

As top priority, 'prevention' of waste refers to the avoidance of waste production and reduction of the generated amount. In second place, 'preparing for re-use' refers to recovery operations like the inspection, cleaning, or repairing of discarded products and their components. Third, 'recycling' applies to any processing operation by which waste is reprocessed into its initial state. Fourth, 'other recovery' refers to any operation where waste is used to replace other materials in order to fulfil a particular function, or where waste is prepared to directly fulfil that function, such as a fuel to generate energy. 'Disposal' means any operation which is not recovery, such as the process of landfilling, and is thus

the one accorded the lowest priority in the waste hierarchy. Even if the respective operation produces energy, for example in the form of landfill gas, it is still considered 'disposal'.

Whether a waste treatment operation is assigned to the category of recovery or disposal is noted within the non-exhaustive lists of Annex I and Annex II of the EU Directive. For instance, Annex I lists as disposal ordinary landfills, especially engineered landfills, incineration, and other operations. Listed recovery operations include composting and other biological transformation processes applied to the waste's organic fraction as well as operations where the waste is principally used as a fuel to generate energy. In order to be classified as a recovery operation the facility's "energy efficiency" has to be equal to or above a threshold. The actual application and interpretation of the formula to determine energy efficiency, also known as the R1 Formula, is supported by European Commission [35] and uses the reference document on "Best Available Techniques for waste incineration" [36]. Nevertheless, the Directive's formula for energy efficiency is not universally applicable. In particular, it disadvantages small installations and warmer countries where plant size and climatic conditions are not taken into account [37]. Furthermore, a change in designation does not necessarily lead to practical consequences, but rather to strong strategic implications and so the policy's intention to stimulate investments into energetic MSW usage comes at the expense of lower classified treatment methods, such as landfills [37].

Energy recovery from MSW and its associated technologies are seen as playing a key role in waste management and renewable energy policy [38]. According to the European Commission [39], who set the targets for the EU's energy policy, all objectives are expected to be achieved by 2020, resulting in a reduction of at least 20% in GHG emissions, an increase in energy efficiency of 20%, a 10% share of biofuels in transport and a 20% share of renewable energies.[7] However, whether and to what extent MSW is regarded as biomass and may therefore contribute to the achievement of these targets depends on the proportions of organic and inorganic components.[8]

2.2. Brazilian legal framework related to solid waste

Brazil's most recent National Policy on Solid Waste (PNRS) has been institutionalised through the federal law 12.305/2010 [26] and regulated by decree 7.404/2010 [41] since 2010. It provides a set of principles, objectives, instruments, guidelines, and directives for the management and exploitation of solid waste and the respective responsibilities of waste generators and the public body. In addition to PNRS, several other federal laws and norms are also directly applicable to the management of solid waste, such as law 11.445/2007 (National Policy on Sanitation), law 9.974/2000 (Law of pesticide and its related components), law 9.966/2000 (Law of oils and other harmful or dangerous substances in waters), and law 6.938/1981 (National Policy on the Environment).

In general, the PNRS aims to establish an environmentally sound solid waste management policy, while addressing all physical persons or legal entities of public or private law that are directly or indirectly responsible for the generation of solid waste. The specific objectives of PNRS are the protection of public health and environmental quality, the integrated management of solid waste, reutilisation and recycling, and the stimulation of the development of environmental management systems and businesses aimed at improving production processes and the recycling of solid waste, including energy recovery [26].

Unlike the EU, which acts as a supra-national institution, influencing its member countries through certain binding instruments, the Federal Republic of Brazil and its federal government share legislative authority through the Brazilian Constitution. Article 21 of Brazil's constitution states that it is the responsibility of the federal government to lay down guidelines for urban development, including housing, sanitation, and urban transport [42]. At the state level, item I of Article 11 of the PNRS, together with the provisions of Section 3° of Article 25 of the Constitution, state that it is the responsibility of the individual federal states to promote the integration, organisation, planning, and execution of public services related to the solid waste management of metropolitan regions, urban agglomerations, and microregions. According to different levels of abstraction, the PNRS' Article 14 lists the following solid waste plans: the "Solid Waste National Plan", the "Solid Waste State Plans", the "Solid Waste Plans for Microregions, Metropolitan Regions, and Urban Agglomerations", the "Intermunicipal Solid Waste Plans", the "Municipal Plans on the Integrated Management of Solid Waste", and the "Solid Waste Management Plans".

Although many different entities in Brazil's public body play key roles in the management of solid waste, it remains the responsibility of each municipality to organise and provide local public services (e.g. urban sanitation) [42,43]. This includes services in public spaces, such as street sweeping and the collection of solid waste from households, including transport, treatment, and final disposal [44]. Likewise, Article 10 of the PNRS expressly states that municipalities are the responsible party for the service of integrated solid waste management in their respective territories. However, decree 7.217/2010 [45] and its underlying law 11.445/2007 [43] state that municipalities may delegate the organisation, regulation, supervision, and provision of the above mentioned services. Felipetto [44] notes three legal vehicles for outsourcing municipal solid waste management:

- Public Procurement under the law 8.666/93 (Public procurement law).
- Granting a Concession according to the law 8.987/95 (Law on concessions).
- Public-Private Partnership (PPP) by law 11.079/04 (Law on PPPs).

Of these, PPP is considered the most suitable model for solving issues related to the management of public services and capable of meeting some of the major administrative challenges of implementing PNRS [46,47]. These challenges include preserving the continuity of public policies in the sector, ensuring resources for sectors where the traditional municipal cleaning fee is too low to achieve economic viability, and creating legal certainty for long-term private investments [44]. PPP effectively combines the traditional strengths of the private sector – dynamism, access to finance, knowledge of technologies, managerial efficiency, and entrepreneurial spirit – with social responsibility, environmental awareness, local knowledge, and job generation within the public sector [48].

However, as Ahmed and Ali [49] noted, partnerships will not be effective and sustainable unless there are incentives for both public and private agencies. Indeed, Article 8 of the PNRS calls for fiscal, financial, and credit instruments aiming at both facilitating and encouraging investments into sustainable waste management technologies including the energetic use of MSW. One such incentive for both solid waste management and environmental considerations is *ICMS Ecolgico* [46,50].

Besides the challenges of its administrative implementation, the PNRS also faces some technical challenges. One such technical challenge is the implementation of the respective waste hierarchy priorities:

(a) prevention,
(b) reduction,

[7] In terms of total energy consumption.

[8] Article 2 of the EU's renewable energy directive states that biomass means the biodegradable fraction of municipal waste [40].

(c) reutilisation,
(d) recycling,
(e) solid waste treatment,
(f) environmentally sound disposal.

Of these, “solid waste treatment” and “environmentally sound disposal” are the most important categories when it comes to energy recuperation. Article 9 states that only proven energy recovery technologies may be used, meaning those that have proven their technical and environmental feasibility and which permit emission monitoring. However, the definitions of the terms “solid waste treatment” (non-defined within the PNRS) and “environmentally sound disposal” are not precise enough to allow the accurate categorisation of energy recovery within the waste hierarchy. The latter term is defined as the orderly distribution of “rejects” in landfills. According to Article 54 of PNRS, environmentally sound final disposal of “rejects” must be implemented within four years of the policy's publication in August 2014. Interestingly, the term “solid waste treatment” in the waste hierarchy refers to “solid waste”, whereas “environmentally sound disposal” relates to material referred to as “rejects”, meaning solid waste which, after having exhausted all technologically available and economically viable treatment and recovery processes, allows no other possibility than environmentally sound disposal.

2.3. Decision criterion for the case study

According to the Brazilian legal framework, solid waste shall pass through reutilisation, recycling, composting, recuperation, recovery, and after all technologically and economically viable processes are exploited, environmentally sound disposal. Assuming that the technological availability of advanced treatment can be ensured, the key criterion in the decision-making process will be the economic viability of facilities. More precisely this will be the cost for the treatment of a specific amount of waste using a particular technology, typically measured in R$/ton. Hence, when choosing among different MSW treatment practices (e.g. between landfill and incineration), the option with the lowest cost is classified higher in terms of the waste hierarchy and will thus be prioritised for practical implementation.

3. Municipal solid waste management in the case of Rio de Janeiro – Case study part I

This section contains an inquiry into final MSW treatment costs in the municipal area of Rio de Janeiro, with its 6 320 446 inhabitants living in a total area of 1200.3 km^2 [51].

3.1. The Comlurb and waste generation

As stated in the previous section, Brazil's municipalities are the responsible party for services related to the management of MSW in their respective territories, including collection, processing and final disposal, but may also delegate these services. In the case of the municipality of Rio de Janeiro, these services are delegated to the “Municipal Urban Waste Cleaning Company”, or Comlurb, which is the largest public cleaning services company in Latin America [46]. Comlurb is a mixed-capital company controlled by the municipality of Rio de Janeiro, its majority shareholder [52]. Arising from the transformation of the Celurb and according to Decree-Law n° 102/1975 [53], Comlurb's main objective is urban cleaning in the municipal area of Rio de Janeiro. This includes, among other services, the cleaning of public spaces (e.g. beaches, public parks, and streets), the collection of household waste (residential, commercial, and industrial), the collection and proper disposal of waste produced by the city's healthcare facilities, and the transfer, treatment, and final disposal of waste [52]. Fig. 1 shows the distribution of the 271.7 thousand tons of waste generated monthly within the municipality of Rio de Janeiro in 2007.

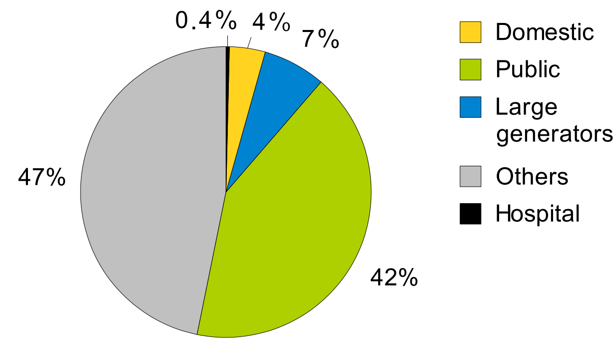

Fig. 1. Distribution of monthly generated waste in the city of Rio de Janeiro in 2007. *Source:* [54].

In addition to the Brazilian legal requirements related to solid waste management (such as PNRS), Comlurb's activities are subject to Rio de Janeiro's federal state laws, such as state law n° 4.191/2003 (State Policy on Solid Waste), and municipal legislation, such as municipal law n° 3.273/2001 (Municipal Law on urban cleaning) and its regulating decree n° 21.305/2002, or municipal law n° 4.969/2008 (Municipal Law on the integrated management of solid waste). Finally, the publication of supplementary law n° 111/2011 (Urban and Environmental Policy of the City) on February 1st, 2011 established the overall plan for sustainable urban development in the municipality of Rio de Janeiro [55,56], including MSW management.

According to Carvalho [46], 81.20% of the company's total operating costs are related to the ordinary activity of urban cleaning. Of this urban cleaning cost, 27.01% represents the collection of household waste, 59.76% are the ordinary cleaning activities in public spaces like sidewalk cleaning, 6.25% are waste transfers, and final disposal totals 6.98%. An inquiry into the prospective financial needs for the management of a certain amount of MSW requires empirical values for historical growth data [57,58]. In 2008, the Comlurb registered an average collection rate of 4320.37 tons per day (tpd) from households and 3513.56 tpd from public spaces, representing an increase of 23.81% and 24.61% respectively compared to rates from 1996 [59]. The historical progression of MSW collection in the municipal area of Rio de Janeiro between 1996 and 2008 is shown in Fig. 2.

3.2. The waste flow and final disposal of collected MSW

After the municipality's waste is collected by Comlurb, the waste is then carried to a number of intermediate stations located within the municipal area of Rio de Janeiro. During the six-month period between January and June 2009, the waste was carried to four intermediate stations. Two of these, Irajá and Caju, are not only waste transfer stations (ETRs), but also function as recycling plants, and the latter is also employed as a composting plant [60]. Caju's annual production of organic compost for the years 2011 and 2012 has been estimated at up to 15 000 m^3 [52]. Another ETR, Jacarepaguá, together with Caju, may be utilised by large generators of MSW. These special clients pay R$ 20 per ton for the first 24 hours of utilisation; after that, they charge the same value, on an hourly basis [60]. The fourth intermediate station used by the Comlurb, Missões, is used for transhipment and sorting. An illustration showing the station's monthly transferred amounts of MSW in the first half of 2009 is shown in Fig. 3. Next to the

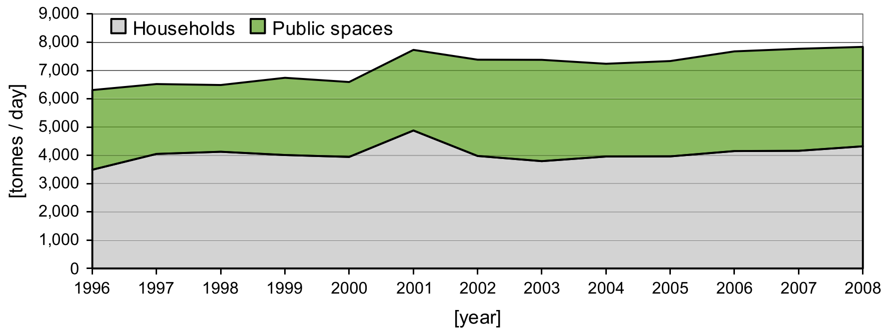

Fig. 2. Average amount of MSW collected daily by Comlurb.
Source: [59].

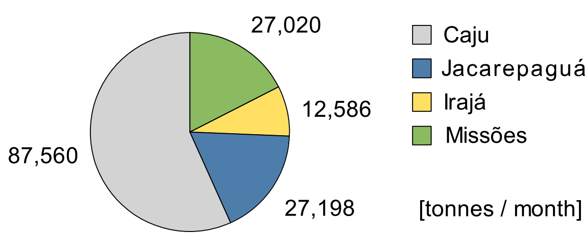

Fig. 3. Monthly transferred amounts of MSW in the first half of 2009.
Source: [61].

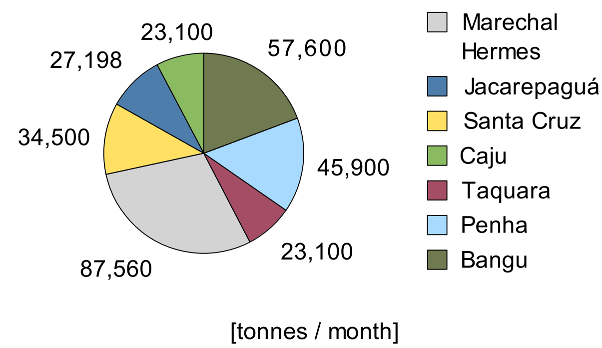

Fig. 4. Expected monthly transferred future amounts of MSW from the seven ETRs.
Source: [61].

processing of MSW through recycling, one of the main objectives of the intermediate stations is the transfer of processed MSW from trucks (mostly compactors and garbage tippers) to higher capacity transports [46]. Subsequently, the output of the four intermediate stations is transported to their final destination at waste disposal sites. On average 823 tpd of waste arising from large generators of MSW is transported from the ETRs of Caju and Jacarepaguá to the solid waste treatment centre (CTR) at Nova Iguaçu. Comlurb transfers the remainder of collected and pre-treated MSW to the Gramacho landfill and the smaller CTR Gericinó, which only received around 24.6% of Comlurb's waste between January and June 2009. Within this 6-month period the Gramacho landfill received 6471 tpd on average, while an average of 2110 tpd was transported to the CTR Gericinó.

Located in the district of Jardim Gramacho, within the municipality of Duque de Caxias and occupying an area of approximately 1 300 000 m^2, the Gramacho landfill was commissioned in 1976 as an open dump [62,63]. Even though its operators started converting it into a sanitary landfill in the early 1990s, the presence of approximately 1700 *catadores* (trash pickers) per day in 2004, justifies its lower classification as a controlled, rather than a sanitary landfill [64]. In 2005, a World Bank study [65] suggested closing the landfill. However, by midyear of 2011, Gramacho is still in service at a gate fee of R$ 14/ton and continues to attract thousands of *catadores* every day [62,60].

The municipality's smaller CTR Gericinó, founded in 1987, is located in the district of Gericinó within the eastern zone of the municipal area of Rio de Janeiro [66]. After being operated as an open dump during the first years of operation, Gericinó is now classified as a sanitary landfill [67]. However, despite the landfill's improvements, especially in the area of applying sanitary engineering methods, minimising environmental impacts, and prohibiting the presence of catadores, Gericinó's operating life technically expired in 2010 [66,59]. In fact, in April 2009 Comlurb [67] published an “Environmental Impact Report” stating that the site's operating life had already reached its final stage, with working capacity for only one more year. The report also considered different scenarios for the extension of the landfill and thus extending the site's operating life. According to the author of the report, the most likely scenario considering technical and environmental norms will be another 6 years of operation. By the midyear of 2011, Gericinó levied a gate fee for non-hazardous waste of R$ 17/ton [60].

The prospective waste flow is to be characterised by a central final disposal site fed by seven intermediate stations. The implementation of both the new CTR and the seven ETRs is the responsibility of a company called Ciclus.[9] Comlurb granted a concession to Ciclus in order to execute the integrated management plan for the transfer, transport, treatment, and final disposal of MSW [68,69]. Moreover, Ciclus' responsibility to the intermediate stations requires the renovation and operation of the two already existing ETRs, Caju and Jacarepaguá, as well as the implementation and operation of five new facilities. The expected monthly transfers are illustrated in Fig. 4. In addition, Ciclus will also be responsible for the transfer of pre-treated MSW from the seven ETRs to the new central CTR.

The second scope of the concession requires the implementation and operation of a solid waste treatment centre that meets the municipality's needs for environmentally sound disposal. Located within the municipality of Seropédica, CTR Santa Rosa will cover an area of 2 212 000 m^2 and is dimensioned to receive 9000 tons of MSW per day with an operating life of 18 years, which is likely to increase[10] [72]. This sanitary landfill is going to apply a leachate treatment plant, soil surface sealing, a landfill gas collection system with electricity generation capable of achieving an installed capacity of some 30 MW, and a flaring system [52]. Santa Rosa has been in operation since 20 April 2011 as a privately operated CTR, and is expected to completely substitute the Gramacho landfill at some point in the future [52].

[9] Ciclus was formed in 2010 as a special-purpose entity that unites the strengths of Júlio Simões SA, a company having logistical experience, with Haztec Novagerar's expertise in waste management [68].

[10] The concession is based on an initial 15-year contract between the Comlurb and a company called SERB (has Ciclus as a kind of fancy name) with the possibility of two further 5-year extensions [70–72].

Indeed, since the Gramacho landfill was shut down on 3 June 2012 after more than 35 years of operation, waste transfers have been directed entirely to the CTRs of Gericinó and Santa Rosa [63]. This change is revealed by the balance [52] for June 2012, which records the average daily amounts of waste received by the three landfills. As a result, Gramacho's landfill accounted for a mere 0.02% of the total 10 363 tpd disposed of, while CTR's of Gericinó and Santa Rosa dominated Comlurb's balance at 2858 tpd and 7503 tpd respectively, or a percentage shares of 27.58% and 72.40%. Therefore, even though the operating life of the CTR Gericinó could potentially be extended for a few more years, the disposal of Comlurb's MSW was provided by CTR Santa Rosa, at an estimated gate fee of R$ 37.20 per ton of MSW by the middle of 2011 [61].

4. Mathematical model for determining the break-even waste price of an energetic waste treatment practice

This section aims to present the methodology used to determine the waste prices when considering future investments into energetic waste treatment practices.

4.1. Methodological approach

According to Maier and Street [73], the process of evaluating the economic feasibility of a single energetic MSW treatment practice, from a private investor's point of view, necessarily requires the economically independent consideration of the related investment project.

In order to ensure the investment's economic viability, Maier and Street [73] applied a net present value (NPV) approach while assuming that the project's NPV reaches zero. By assuming that the investment achieves an NPV equal to zero, subject to the break-even waste price, it follows that the power plant project will achieve the originally expected rate of return, known as the internal rate of return, or IRR. The NPV method is expanded by applying both the Capital Asset Pricing Model (CAPM) and the Lambda Approach, which are used to estimate the asset's rate of return given non-diversifiable risk and the consideration of possible country risks, respectively.

The focus of the methodology is not only to calculate the constant break-even waste price in R$/ton paid to an operator of an energetic waste treatment plant, but also to apply the resultant mathematical model to 20 hypothetical future investment projects starting one per year between 2011 and 2030. The allowance of 20 future investment projects together with the possibility of varying input values for all these 20 investments provides a high degree of flexibility in terms of enabling long-term planning in the field of energetic MSW treatment. The following boundary conditions remain constant over time:

- Time span: the useful life of every power plant is defined as 20 years, starting in year 1 and ending in year 20. Both the approval and the one-year construction time of the energetic MSW treatment plant are considered to occur in year zero of the investment projects. Finally, decommissioning is neglected by the methodology. For example, with regard to the last considered power plant investment project: it will be constructed in 2029, is planned to start operation in 2030, and is projected to run from then on until 2049.
- Inflation: inflation is not considered, or equal to zero.
- Investment: the same investment conditions apply to every investigated project. In addition, plant insurance is not considered within the methodology.
- Power plant revenues: power plant operator gains revenues both from the contractual sale of electrical energy and the stipulated consumption of a specific amount of MSW. An expansion of this base model additionally assumes revenues from the contractual sale of carbon credits.
- TUST and TUSD: it is assumed that an MSW treatment plant with energy recuperation is exempted from paying both the Brazilian transmission fee TUST and the distribution fee TUSD (by applying resolutions of ANEEL [19,20]).
- Other charges: a power plant operator is not required to pay the annual tax TFSEE, ANEEL's supervision fee related to electrical energy services. In addition, it is assumed that there is no tax due for financial transactions and related issues. However, the methodology applies both the "Lucro Presumido" (Presumed Income) and the "Lucro Real" (Actual Income) tax scheme with the following relevant federal taxes: the Corporate Income Tax (IRPJ), the Social Contribution on Net Profits (CSLL), the Social Integration Program (PIS), and the Social Security Contribution (COFINS).

4.2. Input variables

In general, the following input variables are considered to be constant for one specific power plant investment project, even though values may vary when considering different starting investment projects:

- Technological parameters: the economic instance comprises investment costs (in R$), fixed costs (in R$), variable costs (in R $/tons), and, if applicable, operation and maintenance costs (in R$/tons). The technology is characterised by its nominally installed capacity in MW, efficiency in MW h/ton, GHG emission coefficient in tCO_{2e}/ton, and, finally, its capacity factor.
- External financing parameters: characterised by the equity ratio in %, the credit period in years, and the interest rate on debt (in %).
- Discount rate: uses the risk-free rate of interest (in %), the mature market equity risk premium (in %), and the market beta (a decimal number). The Lambda Approach features the additional risk premium due to country risk (in %) and lambda (a decimal number), which measures the exposure of a company to country risk.
- Tax payment function: this category includes the four considered Brazilian federal taxes IRPJ, CSLL, PIS, and COFINS (all percentages).
- Energy price: in R$/MW h, is taken as constant for the 20-year operating life of the power plant.
- Carbon credit price: is modelled as a value in R$ for one metric ton of CO_{2e}.
- CDM specific parameters: CDM investment costs (in R$), CDM fixed costs (in R$/year), and CDM variable costs (as a percentage of generated carbon credits). In addition, this category requires the designation of a constant parameter: the baseline emission (in tCO_{2e}).

4.3. Output variables

The list below describes the output variables, some of which function as state variables, delivered by the mathematical model:

- Produced energy: the yearly generated amount of energy in MW h.
- Treated amount of MSW: the yearly treated amount of MSW in tons/year.
- GHG emissions: both the annual GHG emissions caused by the project activity and the yearly emission reductions in tCO_{2e}.
- Expected return on investment.
- Break-even waste price: the constant waste price in R$/ton paid to an operator of an energy recovery MSW treatment plant where investment in such a plant becomes viable.

4.4. Numerical simulation

The actual numerical simulation uses a cash flow analysis in order to facilitate the calculation of the desired output values, particularly the break-even waste price.

5. Application of the proposed methodology – Case study part II

This section applies the previously presented methodology and mathematical model in order to determine necessary waste prices for hypothetical investment projects according to three different energetic MSW treatment practices.

5.1. Reference scenario

The mathematical model's input variables for a reference scenario, where power plants receive revenues from electricity sales and income from waste treatment contracts, are presented in the following sections.

5.1.1. Technological parameters

With regard to the selection of different energetic waste treatment practices, this scenario agrees with Brazil's National Energy Plan 2030 – PNE 2030 [10]. The technologies considered are Anaerobic Digestion, Incineration, and Optimised Combined Cycle.

Anaerobic Digestion (AD) is a biological treatment process that converts organic materials into a mixed gas consisting mainly of methane and carbon dioxide, known as biogas [74]. The plant is assumed to apply the DRANCO (Dry Anaerobic Composting) process developed in the late 1980s by Organic Waste Systems (OWS), which is particularly suitable for treating the solid and semi-solid organic fraction of waste contained in MSW [75,76]. Thus, the AD plant ideally treats organic waste streams.

The second energetic waste treatment practice is a process of thermal treatment that applies the technology from the USINAVERDE (UV) incineration plant. Both the experimental plant and the surrounding technological centre at UV are located on an area of approximately 5000 m^2 on the campus of Rio de Janeiro's Federal University at Ilha do Fundão, Rio de Janeiro/RJ [77]. Even though UV has been operating since 2005, it is still a prototype plant that generates energy for its own consumption and thus cannot be regarded as a state of the art incineration plant. However, the UV incineration plant has provided interesting operational experience on the subject of MSW incineration in Brazil [78]. Often referred to in the literature as waste-to-energy (WTE), it can be applied to several types of waste, including both mixed and pre-treated MSW, where a high fraction of paper, cardboard, and particularly plastic are beneficial for increasing the fuel input's calorific value and thus the plant's electricity generation [36].

The third technology is the Optimised Combined Cycle (OCC) WTE plant. As its name suggests, OCC is an optimised approach to the traditional combined cycle process initially developed for thermal power stations. The “optimisation” of the combined cycle is necessary because many of the state of the art combined cycle WTE plants that burn natural gas (NG) have an exceedingly high demand for NG, which implies a lower MSW share for the plant and thus contradicts the initial intention of such plants: treating MSW for the purpose of energy generation. Ribeiro and Kimberlin [79] proposed the OCC configuration to greatly reduce the amount of NG needed to increase the efficiency of MSW combustion, allowing the replacement of NG with landfill or biogas from anaerobic digestion.

Table 3 shows the technological parameters' values for the three considered energetic MSW treatment practices. These values are valid, however, only for the first investment project of each considered technological route (i.e. for the AD, UV, and OCC) starting operation in 2011. For the following 19 projects between 2012 and 2030, there is a significant decline of both investment and O&M costs. This results from the fact that investments in power plants, in particular the ones in bioenergy technologies, oftentimes achieve economic benefits through upscaling (economies of scale) and increased technical expertise over time [80].

In fact, according to the data on cost reduction provided by Ea Energy Analyses [81], there will be a 12.50% reduction of capital costs for AD plants between 2010 and 2025, but no further reduction in O&M costs. For the MSW incineration technologies, the UV and the OCC WTE plants the decline of investment and O&M costs is −7.93% and −8.31% respectively for the same period under observation. However, we assume that this total percentage reduction of costs from upscaling and technical expertise will be achieved so that the yearly reductions, if drawn down, lie on a polynomial function of degree 2, rather than as points, for instance, of a linear function. Furthermore, we expand this polynomial approach for cost reductions from 2025 to 2029. Therefore, when compared with power plants built in 2010, the investment costs of an AD plant are modelled to decline by −14.03% by 2029, whereas investment and O&M costs of both an UV and an OCC WTE plant are modelled to decline by

Table 4
External financing parameters. *Source*: Prepared in-house.

Parameter	Value
Equity ratio (%)	20
Credit period (years)	14
Interest rate on debt (%)	11

Table 3
Technological parameters. *Source*: Prepared in-house.

	AD	UV	OCC
MSW capacity (tpd)	360	300	720
Investment costs (R$)	45 000 000	88 366 970	174 000 000
Variable costs (R$/tons)	0	0	27.65[a]
O&M costs (R$/tons)	11.30	49.33	50
Installed capacity[b] (MW)	2.05	5.61	28.73
Efficiency (MW h/ton)	0.164	0.449	0.958
Emission coefficient (tCO_{2e}/ton)	0.0059	0.4418	0.5354
Capacity factor (1)	0.932	0.932	0.912

[a] Represents the additional costs due to NG consumption.
[b] In the case of AD and UV the noted values are representative for exporting energy, hence when considering their own consumption the actually installed capacity increases to 2.5125 MW and 6.6 MW respectively.

−9.00% and −9.43% respectively by 2029. All other technological parameters are assumed to remain constant over time.

5.1.2. External financing parameters

In order to determine the required external financing parameters we employ the financing model provided by the Brazilian development bank BNDES called *Project Finance* [18]. The chosen values for the external financing parameters are shown in Table 4.

5.1.3. Discount rate

For the determination of the necessary discount rate, we used values from Maier [61], which were determined through a case study considering the local conditions of Brazil and mean values from 2010 and 2011 respectively, as shown in Table 5.

5.1.4. Tax payment function

The applied values for the four considered Brazilian federal taxes IRPJ, CSLL, PIS, and COFINS under the Lucro Presumido and Lucro Real tax schemes are shown in Table 6.

Unlike the Lucro Real alternative that calculates IRPJ and CSLL as a percentage of the earning before taxes (EBT) indicator, the Lucro Presumido scheme determines IRPJ and CSLL on a calculation base applied on gross revenues, as shown in Table 7.

5.1.5. Energy price

For the contractual sale of electricity we consider a Power Purchase Agreement (PPA) with a duration of 20 years, which ensures predictable cash flows for power plant operators. As noted by Barroso et al. [84,85], long-term PPA's are a historically well-approved mechanism for the sale of energy. However, by employing R$ 159/MW h in our simulations, we agree with Maier [61] who saw this as a reasonable value for particular investments in the energy sector.

5.2. Scenario with carbon credits

In the second step, power plant investment projects are assumed to receive revenues from energy sales, MSW treatment, and the sale of carbon credits. Therefore, the following sections describe the numerical determination necessary for the scenario with carbon credits.

5.2.1. Carbon credit price

The numerical determination of the carbon credit prices for the 20 projects in each technological route is made according to the expiration of the Kyoto Protocol by the end of 2012, which acts as the CDM's underlying legal regime. As such, carbon credit prices for power plants beginning operation in 2011 and 2012 are determined as R$ 20.70 (€9) per ton of CO_{2e}, and for those starting between 2013 and 2030, the post-2012 CER prices will be modelled in the R$ 13.8–18.4 range (€6–8) [86]. Transactions will be made using an Emissions Reduction Purchase Agreement (ERPA) with a 20-year period of contract, bringing benefits such as more reliable economic forecasts for operators and clear legal regulations for contract parties.

5.2.2. CDM specific parameters

Table 8 summarises the chosen values for the CDM specific parameters assuming low CDM-specific project costs, i.e. those associated with the various stages of the CDM project cycle and the fact that all three technologies apply the same costs related to this issue.

Table 9 shows the yearly constant baseline emission for the considered technologies adapting the baseline emissions from a registered CDM project in the state of Rio de Janeiro called “Brazil NovaGerar Landfill Gas to Energy Project”. A simplified linear approach has been used to transform these baseline emissions to

Table 5
Discount rate. *Source*: Prepared in-house.

Parameter	Value
Risk-free rate (%)	4.69
Equity risk premium (%)	4.50
Market beta (1)	1.54
Country risk premium (%)	4.82
Lambda (1)	1

Table 6
Tax payment function values. *Source*: [82,83].

Type	Lucro Presumido	Lucro Real
IRPJ (%)	15(25)	15(25)
CSLL (%)	9	9
PIS (%)	0.65	1.65
COFINS (%)	3	7.6

Increased values shown in brackets apply for the share of the EBT exceeding R$ 240 000 per year.

Table 7
Calculation base for Lucro Presumido. *Source*: [82].

Activity	IRPJ	CSLL
Energy sales (%)	8	12
Carbon credit sales (%)	8	12
MSW treatment (%)	32	32

Table 8
CDM-specific project costs. *Source*: [61].

Cost type	Value
CDM investment costs (R$)	65 450
CDM fixes costs (R$/year)	8500
CDM variable costs (%)	2

Table 9
Baseline emissions in tCO_{2e} for three considered technologies. *Source*: Prepared in-house and [61].

Technology	Baseline emissions[a]
AD	138 193
UV	125 016
OCC	331 615

[a] Using 0.3095 tCO_{2e}/MW h as emission factor for the Brazilian electricity system to determine the share related to baseline emission from generation of energy.

Table 10
Constant simulation results. *Source*: Prepared in-house.

	AD	UV	OCC
Produced energy (MW h/year)	16 728	45 778	229 603
Treated amount of MSW (tons/year)	122 400	102 000	239 752
Emission reductions (tCO_{2e}/year)	137 468	79 953	203 253
Expected return on investment (%)	16.44	16.44	16.44

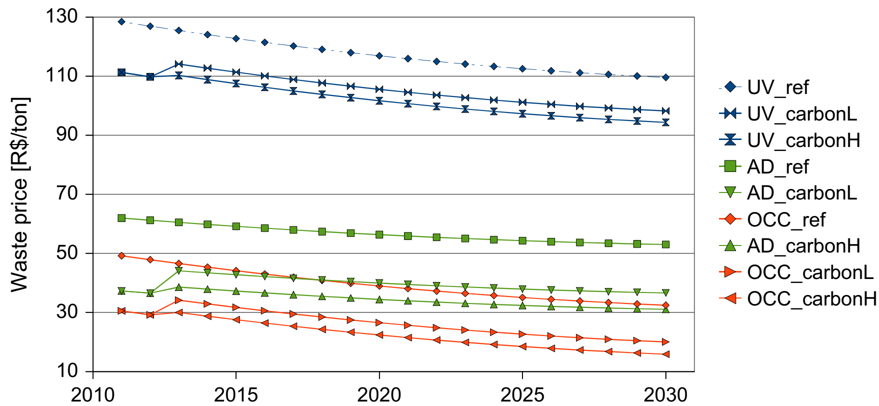

Fig. 5. Solution curves for the reference scenario and the scenario with carbon credits. *Note:* Although representing discrete data, the symbols representing the break-even waste prices of individual power plants, which start operation at various times, are connected by a line for the sake of clarity.

respective technologies, taking into account the daily amount of MSW treated by AD, UV, and OCC treatment plants.

5.3. Sensitivity analysis

The aim of the sensitivity analysis is to identify the influence of the energy and carbon credit price on the break-even waste price. In order to do so, we use power plant investment projects with carbon credits beginning operation in 2011 and modify either the energy price or the carbon credit price within a certain range to see how this alteration affects the model's output, or break-even waste price. The one price not being modified remains constant at the initial value from the underlying scenario with carbon credits.

5.4. Results

Independent from the initial start-up of the three considered energetic MSW treatment practices, several output variables remain constant, where there is no alteration in the related input values. Table 10 lists the constants for the AD, UV, and OCC technologies.

The results from both model runs are shown in Fig. 5. Each point in the figure presents the break-even waste price for a single power plant investment project, or in other words, the necessary price to turn this particular investment into an economically viable power plant. The decline of the waste price over time is due to the fact that cost reductions occur. In addition, the consideration of income from carbon credits shows clear benefits by lowering the necessary gate fees for the considered technologies. As there are two different carbon credit prices for the post-Kyoto Era (i.e. for the time period between 2013 and 2030), there are also two different waste prices for power plants starting operation in the same year. The effective, break-even waste price is expected to reside within this band.

There is a significant difference among the three considered technologies in terms of the required break-even waste price. For example, an energetic MSW treatment technology starting operation in 2011 and using the UV technology in the reference scenario (UV_ref) requires a comparatively high waste price of R$ 128.44/ton in order to be viable. After having received reductions of both investment and O&M costs, a similar plant starting operation 19 years later in 2030 still requires a waste price of R$ 109.50/ton. Even though it has a positive influence on the necessary waste prices, UV's overall competitiveness does not change sufficiently with the additional income from the sale of carbon credits. The first two UV projects of 2011 and 2012 apply R$ 20.70 per ton of CO_{2e} resulting in a gate fee of R$ 111.30/ton and of R$ 109.78/ton respectively, whereas the post-2012 CER prices are either a low value of R$ 13.80/tCO_{2e} or a high value of R$ 18.40/tCO_{2e}, resulting in R$ 114.11/ton (UV_carbonL) and R$ 110.26/ton (UV_carbonH) for an UV plant starting operation in 2013.

On the contrary, the simulation suggests that the AD treatment process results in significantly lower costs for the treatment of a specific amount of waste than UV. This is not clearly indicated in the case of the reference scenario (AD_ref), but is visible when considering additional income from carbon credit sales that replaces the revenues which otherwise would have come from the MSW treatment contract. In the scenario with carbon credits, waste prices decrease to R$ 37.29/ton and R$ 36.54/ton for the first two AD investment projects. Afterwards, post-Kyoto prices lead first to an increase of the gate fee to R$ 44.12/ton (AD_carbonL) and to R$ 38.59/ton (AD_carbonH) for 2013 projects, but decline continuously thereafter.

The third energetic MSW treatment technology, the OCC WTE plant, requires even lower income from the MSW treatment contract and thus has a lower break-even waste price to achieve viability.[11] Waste prices in the reference scenario are on average between 20.58% and 38.76% lower for the 20 considered projects when compared to AD's reference scenario values. The OCC technology not only generates a comparatively large amount of energy per year, but also reduces considerably higher amounts of GHG emissions per year. In fact, the economical consideration of the latter leads to a lower break-even waste price, making it the most competitive technology among the three energetic MSW treatment technologies.

There is also significant difference among the three considered technologies in terms of how strongly each project's break-even waste price is affected by an alteration of revenue streams. Fig. 6 shows the change in break-even waste price subject to a variation in energy price. As we can see, both the UV and OCC incineration technologies, which generate the highest percentage of absolute energy, show a high degree of sensitivity when varying the energy price, meaning that they rely heavily on this source of income.

Especially in the case of OCC, any change of the energy price significantly affects the corresponding waste price. Lowering the energy price below the assumed value of R$ 159/MW h may lead to the OCC technology's competitiveness declining compared to both AD and CTR Santa Rosa. On the other hand, OCC might flourish at an energy price that is higher than the starting value of R$ 159/MW h. In the extreme case of energy prices rising towards R$ 190/MW h, this situation could even lead to a point where OCC

[11] In order to achieve competitiveness for the first investment project of the OCC WTE plant, i.e. the one starting in 2011, a *Lucro Real* exemption was applied. All other projects naturally achieve a taxation in the *Lucro Presumido* tax regime.

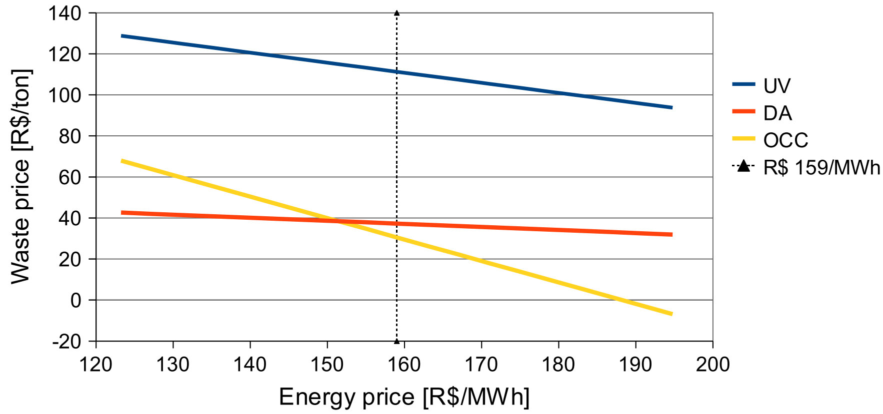

Fig. 6. Results of sensitivity analysis when altering the energy price and fixing the carbon credit price to R$ 20.70/tCO_{2e}.

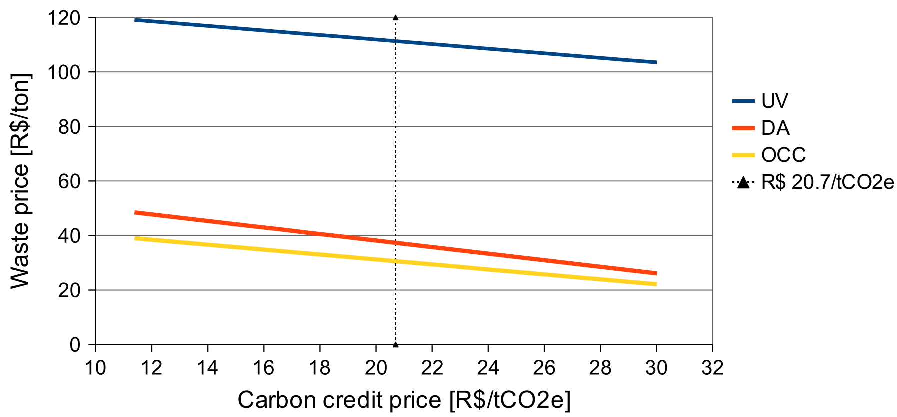

Fig. 7. Results of sensitivity analysis when altering the carbon credit price and fixing the energy price to R$ 159/MW h.

would no longer require a positive waste price to be viable. The UV's initial situation is marked by a high break-even waste price, meaning that even greatly increased energy prices would not lead to a significant decrease in the necessary waste price. The AD technology's behaviour is obviously characterised by its low energy production and thus low sensitivity to changing energy prices, making AD both more independent from this particular source of income, but also less beneficial in terms of price jumps.

Even though the necessary waste prices for each technology drop when allowing additional revenues from CER sales, there is significant difference among the three technologies and the drop in waste price they achieve. The influence of altered CER prices on the break-even waste prices is shown in Fig. 7. Unlike in the case of the energy price's alteration, in this second sensitivity analysis, AD is the most sensitive technology. Like OCC in the previous sensitivity analysis, a change in carbon credit price can either be beneficial, meaning waste prices drop when CER prices rise, or unfavourable. The OCC WTE plant's break-even waste price is still more sensitive to altered CER prices than the UV plant, which is not, however, competitive in terms of its waste price.

6. Discussion

Given the main objective of the case study, economic feasibility of energetic MSW treatment practices has to be assessed in the light of Brazil's PNRS, and in particular, the state of final MSW disposal in Rio de Janeiro (currently represented by CTR Santa Rosa). As such, the considered AD, UV, and OCC technologies need to represent economically viable processes in order to be ranked higher than the CTR Santa Rosa within the waste hierarchy, and thus be able to replace lower ranked categories of disposal. Comparing the single break-even waste prices of Fig. 5 with the gate fee of the CTR Santa Rosa in the amount of R$ 37.20/ton shows the configurations under which the three considered energy recuperation technologies are competitive. Table 11 lists (where existing) the year when the respective waste price of each project is predicted to underrun Santa Rosa's landfilling costs. The impressions gained by the comparison of the simulation results reflect, to some extent, the technologies' overall standing in terms of their competitiveness. The projects applying the UV technology are not competitive compared to the other two energetic treatment practices or landfilling.

In the case of the simulated AD power plants, however, the situation is different. Although not viable in the reference scenario, the addition of revenues from the sale of carbon credits makes the AD technology viable as early as 2012, meaning that relatively high CER prices make the AD plant starting operation in 2012 economically viable. Nevertheless, the drop of post-2012 CER prices necessitates a higher portion of the AD's income from waste treatment, which in turn necessitates higher waste prices. Depending on the modelled value of the post-Kyoto CER price, AD plants are unlikely to be viable until 2016 (AD_carbonH) and 2028 (AD_carbonL).

By comparison, investment projects using the OCC technology achieve viability in the reference scenario and the scenario with carbon credits. In the first case (OCC_ref), an OCC WTE plant starting operation in 2023 would underrun Santa Rosa's costs of R$ 37.20/ton. However, adding carbon credits as a revenue source leads to OCC_carbonL and OCC_carbonH becoming viable as early as 2011, meaning that the first projects will be economically viable. Therefore, regardless of the unfavourable trend of carbon credit

Table 11
Conditions of economic feasibility. *Source*: Prepared in-house.

Scenario	Year[a]	Waste price[a] (R$/ton)
UV_ref	–	–
UV_carbonL	–	–
UV_carbonH	–	–
AD_ref	–	–
AD_carbonL	2012/2028	36.54/37.04
AD_carbonH	2012/2016	36.54/36.63
OCC_ref	2023	36.48
OCC_carbonL	2011	30.54
OCC_carbonH	2011	30.54

[a] Pre/Post-Kyoto.

prices after 2012, the OCC WTE plants remain viable in both situations (i.e. OCC_carbonH and OCC_carbonL).

As Table 10 shows, a direct comparison of the results obtained by different technologies is misleading due to the fact that it does not consider the different sizes of the plants, usually related to the plant's capacity in tpd. Indeed, the OCC WTE plant's dominance in terms of MSW treatment and emission reduction is due mainly to its larger size, which is 720 tpd and thus almost twice as large as either the AD and UV plants at 360 tpd and 300 tpd respectively. Nevertheless, the OCC's advantage in energy generation – generating almost 14 times as much per year as AD and five times as much as UV – cannot be justified by plant capacity alone. Rather, it accrues from the plant's significantly higher waste-to-energy efficiency. On the other hand, AD's emission reduction ratio per ton of MSW treated is highest at 1.123 tCO_{2e}/ton, whereas UV and OCC achieve reductions of 0.784 tCO_{2e}/ton and 0.848 tCO_{2e}/ton respectively.

Ideally, the decision of whether to choose a particular MSW treatment practice over another would depend exclusively on their respective classification in the waste hierarchy. The EU's Waste Framework Directive clearly declares the conditions under which a solid waste treatment operation is assigned to the category of recovery (including energy recovery) or to the lower ranked category of disposal. By comparison, although Brazil's National Policy on Solid Waste generally allows the use of technologies for energy recovery from MSW, it lacks a clear categorisation for prioritisation. Indeed, considering the Brazilian waste hierarchy, the explanation of the relevant categories “solid waste treatment” and “environmentally sound disposal” is vague in their wording. This results in there being no clear distinction between different treatment facilities, such as between dedicated energy recovery facilities and landfills (although the latter ones might apply biogas recovery). Therefore, the so-called waste hierarchy is very likely to preserve the state of things in Brazilian MSW management, rather than lead to sustainable disposal with supplemental energy generation.

On the practical and legal side of the argument, the solid waste management market contains a number of stakeholders. The market for urban cleaning services exceeds R$ 19 billion and employs a large number of waste pickers, directly employing almost 300 thousand workers in 2010 [4]. In addition to the country's PNRS, there are a myriad of further solid waste plans limiting both the effectiveness and efficiency of proper MSW management. However, in the end, the municipalities are the primary stakeholders of integrated solid waste management in their respective territories, and it is they who are primarily responsible. Rio de Janeiro has a long history of dependence on landfill for the purpose of final MSW disposal. Indeed, the newly built CTR Santa Rosa is expected to run for at least another 25 years, and given the past experience on extending the useful life of Rio's landfills, it can be expected that it will be in service even longer.

Unlike the EU's Directive 1999/31/EC on landfilling, there is very little regulation on landfilling in Brazil, leading indirectly to their ubiquity. Nevertheless, Brazil's PNRS calls for the implementation of “environmentally sound disposal” by mid-2014, which will (if the low cost level of landfills in Brazil can be maintained in future installations) most likely lead to the construction of more advanced landfills, such as sanitary landfills, rather than to the construction of energy from waste facilities. Even though the gate fees of new landfill sites have increased during the last few decades because of their increased overhead (CTR Santa Rosa levies an estimated gate fee of R$ 37.20/ton compared to the nearly 25 year old CTR Gericinó at R$ 17/ton), they are still comparatively cheap and thus competitive when compared to the three energetic MSW treatment practices in our case study. Hence, considering monetary aspects and neglecting other influencing factors such as environmental impacts, land availability, socio-economic benefits, and energetic potential, it is very likely that Brazil and Rio de Janeiro in particular are looking at a future of unsustainable MSW disposal and treatment.

In general, the operator of an energetic MSW facility will receive revenues from a number of different streams and thus compete on different markets. Minimising investment risks and ensuring predictable capital flows are of particular importance for new investments in this field. In terms of MSW contracts, Brazil‘s municipal governments may outsource their obligations through a number of legal avenues, whereas the literature suggests that PPPs in particular will play a central role in contracts with Brazilian municipalities. However, competition for revenues from these sources means competing with low cost landfills.

In the case of selling electrical energy through PPAs, waste treatment technologies like the AD, UV, and OCC plants considered in this study have to compete in the Brazilian energy market, which has been traditionally dominated by large centralised hydroelectric power plants. In particular, technologies like the OCC WTE plant that are highly sensitive to electricity prices may be strongly affected by this competition. Hence, depending on the economic climate, it might be interesting to explore natural gas markets, for instance in the case of an AD plant that can serve Brazil‘s fuel needs in transportation.

The third type of revenues considered within the case study arose from the sale of carbon credits through ERPAs. CER prices are strongly linked to international carbon markets and their fluctuations. However, market uncertainty in these areas due to doubts about the post-Kyoto Era makes them highly unreliable sources of income for achieving economic feasibility. Not considered within the case study, but having particularly advantageous benefits for the overall performance of facilities and economic feasibility, is the utilisation of the heat from the combustion process as an additional source of income [87–90].

Apart from the fact that Brazil's PNRS sets the framework for financial incentives encouraging investments into new technologies, there are a number of additional incentives designed and implemented long before the PNRS came into force. As such, considering the tenuous achievements of previous investment initiatives aiming to promote biomass, such as those of the expired PROINFA, or those of BNDES's *Project Finance* programme, there is great uncertainty about whether future investments into renewable energy sources will automatically lead to increased energy production from biomass and MSW. Despite its ambitious goals, the biomass sector is either under-represented, or if there is a satisfactory number of projects realised, almost all are using sources like sugar cane bagasse, black liquor, firewood, and rice husk, rather than the non-conventional renewable resource of MSW. As shown by our simulations, applying the existing incentives to investment projects does not necessarily ensure that the best available technologies are competitive with traditional

landfilling. In fact, our simulated investment projects considered incentives provided through the BNDES's *Project Finance* programme, the former PROINFA's average energy price of R$ 159/MW h, as well as ANEEL's investment incentive, meaning an exemption from both transmission fee TUST and distribution fee TUSD. Despite all these measures, additional cost reductions in these technologies like those considered within our case study (upscaling and increased technical competence) and beneficial influences like institutional learning are badly needed in order to improve the economic feasibility of energetic MSW treatment plants.

The successful integration of different energetic MSW treatments into the municipalities' solid waste management strategies must consider the needs of both the integrated waste management and the sustainable expansion of the electricity sector [91,21]. This should be considered when identifying suitable sites, the optimal scale and the number of plants during the decision making process (e.g. using Geographical Information Systems [90]). In the case of the municipality of Rio de Janeiro, the collected MSW is primarily transported to a number of intermediate stations, all of which have different treatment capacities (i.e. receiving different amounts of MSW) and are distributed throughout the municipality. Issues like energy demand (both heat and power) and logistics costs will therefore have a great impact on the site location. Moreover, given that the OCC WTE plant may use biogas coming from either landfills, such as CTR Santa Rosa, or AD plants treating the MSW's organic fraction, there may also be additional operational interconnections among different facilities [89].

7. Conclusions

7.1. Implications of model results

In the case of Rio de Janeiro, applying the decision criterion provided by the Brazilian legal framework does not necessarily contribute to the successful replacement of landfills with MSW treatment facilities using energy recovery. In the case of the municipality of Rio de Janeiro, the final disposal of MSW is historically dominated by centralised landfills served by a small number of waste transfer stations. After the long-awaited shutdown of the Gramacho landfill in mid-2012, the municipality's MSW has been mainly disposed of at CTR Santa Rosa located within the municipality of Seropèdica. Given past experience with lifetime extension, the Santa Rosa landfill can be expected to remain in service for decades. However, there are some configurations under which the AD and OCC WTE plant can be competitive compared to the Santa Rosa landfill in terms of gate fee. As our simulations have shown, when considering revenues from both electricity and carbon credit sales, in addition to the revenues from the stipulated consumption of a specific amount of MSW, both the AD and OCC WTE plants could achieve economic feasibility. On the other hand, considering electricity sales alone and neglecting CER sales allows the OCC WTE technology to become feasible, whereas the AD technology is not.

In addition to competing for waste treatment contracts with the municipal government, the economic feasibility of energetic MSW treatment facilities also depends on their competitive strength in other markets. Given the different characteristics of the considered technologies with regard to their GHG emission reduction and energy generation potential, there is a significant difference between the power plants' vulnerability to both low electricity and CER prices. In the case of the Brazilian electricity market, which is historically dominated by large centralised hydroelectric power plants, the OCC WTE plant, having the best waste-to-energy efficiency of all considered technologies, is particularly exposed to price level risk. On the contrary, having the most beneficial environmental impact in terms of GHG emission reductions, the AD plant's break-even waste price is particularly dependent on the price level of international carbon markets. However, given the uncertainties of those markets in the post-Kyoto Era, relying on potential revenues from CDM registration when assessing the economic feasibility of energetic MSW treatment facilities is highly questionable.

7.2. Strategic and policy implications

Given the identified shortcomings of Brazil's new National Policy on Solid Waste with respect to investments into energy recovery, the successful market entrance of modern MSW solutions will require further encouragement of private investments in the field. When compared to the EU's waste legislation in particular, the Brazilian counterpart maintains a poorly defined waste hierarchy which is most likely to maintain the country's unsustainable status quo in terms of final MSW disposal, rather than leading towards a paradigm shift in solid waste management.

It appears that the main breakthrough required is not technical. What is required is of a regulatory and financial nature. Having a variety of underlying laws and policies, the PNRS sets rules for various public and private sector protagonists acting in the field of solid waste management. Given the policies' lack of ambitious goals at the federal level, state and municipal governments should take the initiative of driving through badly needed reforms in the Brazilian waste market. In fact, in order to be higher classified within the waste hierarchy, it is essential for facilities recovering energy from MSW to be economically viable. However, given the comparative dearth of landfilling regulation in Brazil and its comparatively low costs as a disposal method, the economic feasibility of plants using energy recovery from MSW is difficult to achieve. As a result, simply applying existing financial incentives to investments into renewable energy projects in Brazil, as in the presented case study, does not ensure economic viability of advanced technologies without considering cost reductions or tax harmonisation. Therefore, financial incentives rewarding the construction of energy from waste plants are needed to have a significant impact on investment decisions. In terms of risk management, long-term PPA auctions and ERPAs are tried and tested mechanisms that ensure predictable revenues for both renewable electricity and carbon credits. Moreover, the PPP has been shown to be an increasingly important legal vehicle for contracting with the municipal government.

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